ELSEVIER Journal of Hazardous Materials A103 (2003) 25–40

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Case study

Integrated risk analysis for acute and chronic exposure to toxic chemicals

B.R. Gurjar[a], Manju Mohan[b,*]

[a] *Max Planck Institute for Chemistry, Atmospheric Chemistry Division,*
P.O. Box 3060, D-55020 Mainz, Germany
[b] *Centre for Atmospheric Sciences, Indian Institute of Technology, Hauz Khas, New Delhi 110016, India*

Received 13 August 2001; received in revised form 4 July 2003; accepted 8 July 2003

Abstract

The traditional practice to assess and evaluate different types of risk in isolation to each other are liable to give erroneous results. Integrated risk assessment is an answer to overcome this problem. This paper presents the cumulative or integrated assessment of acute risk posed by accidental release of hazardous chemical (e.g. chlorine) and chronic risk induced by toxic chemicals (e.g. cadmium, chromium and nickel) present in the ambient environment. The present study has been carried out in a most simplified way to demonstrate and appreciate the broader context of integrated risk analysis (IRA). It has been observed that the inclusion of background risk factors (BRF) in individual risk factors (IRF) related to an industry may significantly alter the siting and planning strategies of that industry.

Keywords: Integrated risk analysis; Acute risk; Chronic risk; Toxic chemicals; Heavy metals

---

1. Introduction

The general practice to study various types of risk in isolation to each other could give erroneous conclusions. This is because in real life situations, a person or community may encounter the combination of occupational and environmental risks posed by the surrounding. For example, in addition to accidental releases of extremely hazardous chemicals, the continuous exposure to toxic pollutants released from industrial facilities and other anthropogenic activities may also cause adverse effects on human health and the environment [1]. Besides the assessment of acute risks posed by industrial accidents, it is therefore necessary

---

* Corresponding author. Tel.: +91-11-2659-1313; fax: +91-11-2659-1386.
E-mail addresses: mmanju@cas.iitd.ernet.in, mmohan6@hotmail.com (M. Mohan).

doi:10.1016/S0304-3894(03)00228-0

Table 1
Risk ranking matrix (RRM) for identification of suitability of industries on the basis of IRF and GSRF values [2]

GSRF (km^{-2} per year)-based site category as risk zones	IRF (per year)-based risk potential of industries			
	High risk (IRF $> 10^{-4}$)	Medium risk ($10^{-4} >$ IRF $> 10^{-5}$)	Low risk ($10^{-5} >$ IRF $> 10^{-6}$)	Very low risk (IRF $< 10^{-6}$)
Low-risk zone (GSRF $< 10^{-3}$)	CS	S	S	S
Medium-risk zone ($10^{-3} \leq$ GSRF $< 10^{-2}$)	U	CS	S	S
High-risk zone ($10^{-2} \leq$ GSRF $< 10^{-1}$)	U	U	CS	S
Severe risk zone (GSRF $> 10^{-1}$)	U	U	US	CS

U, unsuitable; CS, conditionally suitable; S, suitable.

to assess the chronic health aspects of pollutants [2], too, as it costs to the society in the form of demands on medical resources, poor health, and the impact of loss of productivity and ultimately of premature deaths [3]. Integrated risk analysis, as practiced in California for over a decade [4–7], and now increasingly becoming popular worldwide [2], is a suitable tool to use in such situations.

A cumulative or integrated approach of environmental risk analysis (ERA) has been proposed and used in this study to unify the toxic risks experienced by general population living in the vicinity of industries using hazardous chemical, e.g. chlorine, and also exposed to the ambient atmospheric environment contaminated with heavy metals, e.g. cadmium, chromium and nickel. The approach suggested in this study is an illustrative one and in reality there may be other toxics in the plant or background which are not explored for the sake of simplicity.

To begin with, individual risk factors (IRF) and geo-societal risk factors (GSRF) have been estimated for two hypothetical Indian industries that may cause acute risk due to an accidental release of chlorine in the atmosphere [2]. In addition, background risk factors (BRF) have been determined by converting the chances of extra cancer cases into mortality per year. The cumulative individual risk factors (CIRF) and cumulative geo-societal risk factors (CGSRF) have been calculated as the sum total of risks posed by acute and chronic toxic exposures. On the basis of these cumulative risk factors (i.e. CIRF and CGSRF) and risk ranking matrix (Table 1), the suitability of two hypothetical industries has been evaluated. It has been observed that while evaluating risk in cumulative or integrated manner giving due consideration to background risk estimates, the suitability of industries get changed in comparison to its status decided by risk factors belonging to merely accidental release of chlorine from their storage facilities.

2. Need and scope of integrated risk analysis

It is increasingly being recognized that an estimation of the exposure of the population to air pollutants is more relevant than the ambient air quality, since it gives a better indication of health risk [8]. A host of pollutants, individually as well as in combined form, through single and/or various exposure routes may result in different kinds of health risk to the receptors. In academia as well as industry, however, there has been a dominion of risk assessment approaches that focus on one type of risk posed by a single chemical in a single medium. For example, it may require to assess fatality occurred due to an airborne toxic release into atmosphere, or chances of cancer and subsequent deaths due to chronic exposure to a particular carcinogenic substance through inhalation or ingestion in isolation to each other. While these approaches have assisted to achieve some progress in reducing health, safety and environmental risks in recent decades, they are often considered inadequate to address more complex risk problems in their larger and real world contexts. As the public awareness has increased across the world, technical issues facing the regulatory agencies responsible for environmental protection and pollution control has become increasingly complex. As a result, the need to assess and evaluate more than one risk in an integrated manner has been equally realized and recognized by stakeholders, researchers and the policy makers. Clearly, new perspectives and new approaches are needed to manage risks effectively in present society [9].

An approach of integrated risk analysis (IRA) has been proposed and used in this paper to study the cumulative effect of acute and chronic (carcinogenic as well as non-carcinogenic) risks on the suitability of two hypothetical industries located in particular geographical regions. The proposed IRA approach considers multidimensional aspects of risk assessment. These aspects include risks in multimedia (e.g. air, water, and food), multi-routes (e.g. through inhalation as well as ingestion), multi-chemical (e.g. chlorine, cadmium, chromium, and nickel), and multi-risk (e.g. acute, chronic, carcinogenic, and non-carcinogenic) contexts.

3. Materials and methods

Risk can be presented in the form of various parameters [10]. In general, health risk is defined as the probability that an individual exposed to a pollutant may experience an adverse health effect subsequent to the exposure [6]. However, in the analysis of risks both the magnitudes of the probabilities and of the consequences are of importance. A risk measure is defined as a mathematical function of the probability of an event and the consequences of that event [11]. Most risk measures, such as individual risk factors, can thus be expressed with a mathematical formulation. Nonetheless, risk assessment tools, e.g. multimedia models do not provide absolute estimates of risk [12]. Instead, these methods produce conditional estimates based on multiple assumptions made by the risk assessor during the risk assessment process [13,14]. When applied to multiple problems or different approaches at the same site, these conditional estimates are termed ‘relative risks’ [12].

In present study, mean concentration levels of Cd, Cr and Ni, as reported by Krishnamurti and Vishwanathan [15] have been used to estimate the individual and societal risks of extra cancer and other adverse health effects in different states of India. The population data of different states were taken from Mahendra [16] to calculate incremental individual cancer risk related to cadmium, chromium and nickel contamination present in certain atmospheric environments in India. The carcinogenic risk estimates were made using classical dose–response model [17,18] as discussed and applied by the authors in another publication [19]. These risk estimates have been termed as background risk factors.

The individual risk factors and geo-societal risk factors (GSRF) related to a catastrophic release of chlorine from two hypothetical industries has been estimated using IIT-QRA model [2]. IIT-QRA model calculates IRF using the following probit relationship [20] for toxic gases:

$$P_r = a + b\ln(C^n t) \tag{1}$$

where the weighting on concentration, C, appears in the dose criterion index, n. The duration of exposure is, t, and the coefficients (i.e. a and b) express the positions of families of mortality levels (LD5, LD50, LD95, etc. which are lethal doses responsible for 5, 50, and 95% mortality) on a graph of, C versus t [21].

The probit relationship may be applied to various circumstances in which a population (not necessarily human) may be expected to show varying susceptibility to some stressing agent. It was largely developed in the context of tests on the effectiveness of insecticides as described by [22]. The probit, P_r, is a normally distributed variable with a mean of 5 and a standard deviation of 1. It is so that for a population exposed to certain combinations of, C, and, t, the percentage mortality is approximately 16% for $P_r = 4$, 50% for $P_r = 5$, 98% for $P_r = 7$, and so forth [21].

Further, the cumulative risk factors have been estimated by summing up background risk factors with risk estimates derived from IIT-QRA model. Here total risk is computed by adding the risk via each pathway (as in Kumar et al. [6]), and summing up the acute and chronic risk estimates. It has been assumed that their effect is additive but not the synergistic. Finally, on the basis of various estimated risk factors, the suitability of industries in the given geographical location has been evaluated using the risk ranking matrix [2,23].

4. Integrated risk analysis of two hypothetical Indian industries

Two hypothetical industries located in Haryana state of India have been considered for this study. These are (i) M/s XYZ-1 Ltd., Bahadurgarh (Haryana), and (ii) M/s XYZ-2 Ltd., Yamuna Nagar (Haryana). These industries have been assumed with the following distinct features.

4.1. M/s XYZ-1 Ltd., Bahadurgarh (Haryana)

This industry is assumed to be situated in Bahadurgarh, which is an industrial town of Haryana (India). This town is located at the periphery of New Delhi, the national capital state of India. M/s XYZ-1 Ltd. supposedly manufactures chlorinated paraffin vaccine for which it keeps storage of chlorine in a pressurized vessel of 5400 kg capacity. The industry is about 2 km away from national highway and approximately 6 km away from forest-land. Moreover, population density is approximately 568 people/km^2 up to 3 km from its location. Beyond 3 km there is an urban area, which has population density equal to about 6359 km^{-2} [24].

Table 2
Failure frequency data [29,30]

S. No.	Item	Failure frequency ($\times 10^{-6}$ per year)
1	Process/pressure vessel shell failure	3
2	Pressurized storage vessel shell failure	1
3	Refrigerated storage tank shell failure	0.3
4	Full bore vessel connection failure (diameter in mm)	
	<25	30
	40	10
	50	7.5
	80	5
	100	4
	>150	3

4.2. M/s XYZ-2 Ltd., Yamuna Nagar (Haryana)

This industry is considered as a paper mill located in the heart of the city Yamuna Nagar surrounded with a dense population of density equal to about 3466 km^{-2} up to 3 km. Beyond 3 km from the concerned industry, rural area exists having approximately 539 people/km^2. The industry keeps storage of 20,000 kg of Cl_2 in a refrigerated storage tank at $-10\,^{\circ}$C. Yamuna Nagar is also an industrial town of Haryana state of India. The population data for both the industries have been adopted from the publications of Economic and Statistical Organization, Planning Department, Government of Haryana [24].

Described as above, both industries differ from each other in the manner of storage of chlorine, location and pattern of population distribution around the industry. As per failure frequency data shown in Table 2, the failure frequency in case of first industry has been taken equal to 1×10^{-6} per year, while in case of M/s XYZ-2 Ltd., it has been considered as 0.3×10^{-6} (or 3×10^{-7}) per year. It is assumed that the refrigerated storage tank at M/s XYZ-2 Ltd. is equipped with necessary safety mechanisms to keep its failure frequency as low as 0.3×10^{-6} per year. The source of Table 2 is from two Indian organizations which perhaps may have used the data of similar plants to derive failure frequencies. This is often practiced if statistics from a single plant is inadequate or plant is not old enough to generate sufficient data to estimate this. In any case the estimates can be considered reasonable as far as the present study is considered. As shown in Tables 3 and 4, individual risk factors at different downwind distances have been estimated for each industry using IIT-QRA model. IRF have been estimated for F-stability weather condition. Three-wind speeds equal to 2, 1.6 and 1 m/s were considered for estimations. IRF belonging to 1 m/s wind speed and corresponding population density have been used for further calculations of GSRF as shown in Tables 5 and 6. Subsequent evaluation of suitability of these industries, as shown in Tables 5 and 6, was carried out using the IRF and GSRF estimates and risk ranking matrix (see Table 1). Wind speed equal to 1 m/s has been chosen because at present State Pollution Control Boards of Haryana and Punjab states are known to use this wind speed in risk assessment studies. Moreover, it is also a fact that low wind conditions frequently occur in tropical countries like India. It has been

Table 3
IRF at selected downwind distances for a hypothetical catastrophic release of chlorine from the premises of M/s XYZ-1 Ltd., Bahadurgarh (Haryana)

Downwind distance (km)	IRF corresponding to different wind speeds		
	IRF (year), when wind speed = 2 m/s	IRF (year), when wind speed = 1.6 m/s	IRF (year), when wind speed = 1 m/s
0.10	1.47E−5	1.49E−5	1.54E−5
0.20	1.41E−5	1.44E−5	1.50E−5
0.30	1.30E−5	1.34E−5	1.42E−5
0.40	1.17E−5	1.22E−5	1.31E−5
0.50	1.04E−5	1.09E−5	1.20E−5
1.00	5.63E−6	5.97E−6	7.06E−6
2.00	2.25E−6	2.37E−6	2.53E−6
3.00	4.87E−7	5.89E−7	7.43E−7
3.40	0.00	5.31E−8	2.13E−7
4.00	0.00	0.00	0.00

Input data: Storage facility = 5400 kg of pressurized chlorine; instantaneous release of Cl_2 = 5400 kg; ambient temperature = 20 °C; weather stability = F; failure frequency = 1×10^{-6} per year. Risk assessment tool: IIT-QRA model.

observed that in Delhi, the calms occur about 40% of the time [25]. As both the industrial towns considered in this study, i.e. Bahadurgarh and Yamuna Nagar, are the towns of Haryana which is a north-Indian state adjoining to Delhi, it was justified to choose wind speed equal to 1 m/s in the present study from technical as well as regulatory point of view.

Table 4
IRF at selected downwind distances for a hypothetical catastrophic release of chlorine from the premises of M/s XYZ-2 Ltd., Yamuna Nagar (Haryana)

Downwind distance (km)	IRF corresponding to different wind speeds		
	IRF (year), when wind speed = 2 m/s	IRF (year), when wind speed = 1.6 m/s	IRF (year), when wind speed = 1 m/s
0.1	4.53E−6	4.59E−6	4.71E−6
0.2	4.48E−6	4.55E−6	4.70E−6
0.3	4.35E−6	4.43E−6	4.61E−6
0.4	4.12E−6	4.23E−6	4.45E−6
0.5	3.87E−6	3.99E−6	4.25E−6
1.0	2.62E−6	2.79E−6	3.15E−6
2.0	1.30E−6	1.35E−6	1.44E−6
3.0	7.46E−7	7.73E−7	8.10E−7
4.0	3.76E−7	4.01E−7	4.35E−7
5.0	9.47E−8	1.20E−7	1.57E−7
5.5	0.00	9.48E−10	3.94E−8
6.0	0.00	0.00	0.00

Input data: Refrigerated storage of Cl_2 = 20,000 kg (at −10 °C); scenario = burst of the storage tank; ambient temperature = 20 °C; weather stability = F; failure frequency = 0.3×10^{-6} per year. Risk assessment tool: IIT-QRA model.

Table 5
Determination of risk potential and suitability of M/s XYZ-1 Ltd., Bahadurgarh (Haryana) on the basis of IRF and GSRF estimates at selected downwind distances in the given region

Downwind distance (km)	Population density (km^{-2})	IRF (per year) when wind speed = 1 m/s	GSRF (km^{-2} per year)	Suitability[a] evaluation as per risk ranking matrix (Table 1)
<0.5	568	1.54E−5 to 1.20E−5	8.74E−3 to 6.82E−3	CS
0.5–1.0	568	1.20E−5 to 7.06E−6	6.82E−3 to 4.01E−3	CS
1–2	568	7.06E−6 to 2.53E−6	4.01E−3 to 1.44E−3	S
2–3	568	2.53E−6 to 7.43E−7	1.44E−3 to 4.22E−4	S
3.0–3.4	6359	7.43E−7 to 2.13E−7	4.72E−3 to 1.35E−3	S
>3.4	6359	<2.13E−7	<1.35E−3	S

Input data: Storage facility = 5400 kg of pressurized chlorine; instantaneous release of Cl_2 = 5400 kg; ambient temperature = 20 °C; weather stability = F; failure frequency = 1×10^{-6} per year; wind speed = 1 m/s; population density around the industry = 568 km^{-2} (rural) up to 3 km, and 6359 km^{-2} (urban) beyond 3 km; distance to national highway = 2 km; distance to residential area = 3 km. Risk assessment tools: IIT-QRA model and risk ranking matrix.

[a] CS, conditionally suitable; S, suitable.

Table 6
Determination of risk potential and suitability of M/s XYZ-2 Ltd., Yamuna Nagar (Haryana) on the basis of IRF and GSRF estimates at selected downwind distances in the given region

Downwind distance (km)	Population density (km^{-2})	IRF (year) when wind speed = 1 m/s	GSRF (km^{-2} per year)	Suitability[a] evaluation as per risk ranking matrix (Table 1)
<0.5	3466	4.71E−6 to 4.25E−6	1.63E−2 to 1.47E−2	CS
0.5–1.0	3466	4.25E−6 to 3.15E−6	1.47E−2 to 1.09E−2	CS
1–2	3466	3.15E−6 to 1.44E−6	1.09E−2 to 4.99E−3	CS
2–3	3466	1.44E−6 to 8.10E−7	4.99E−3 to 2.81E−3	S
3–4	539	8.10E−7 to 4.35E−7	4.37E−4 to 2.34E−4	S
4–5	539	4.35E−7 to 1.57E−7	2.34E−4 to 8.46E−5	S
>5	539	<1.57E−7	<8.46E−5	S

Input data: Refrigerated storage of Cl_2 = 20,000 kg (at −10 °C); scenario = burst of the storage tank; ambient temperature = 20 °C; weather stability = F; failure frequency = 0.3×10^{-6} per year; wind speed = 1 m/s; population density around the industry = 3466 km^{-2} up to 3 km, and 539 km^{-2} beyond 3 km. Risk assessment tools: IIT-QRA model and risk ranking matrix.

[a] CS, conditionally suitable; S, suitable.

5. Background individual risk factors (BIRF)

Those who live in the vicinity of chemical industries are not only vulnerable to acute risk posed by possible industrial accidents, but they also constantly get exposed to an additional background risk induced by the presence of toxic pollutants such as Cd, Cr and Ni in the ambient environment. A toxic pollutant might find its way into the human body through more than one pathway [7]. Thus, the background concentration of toxic pollutants pose a potential threat to enter the human body through the intake of contaminated air, water and food supply available to the community. In present study, therefore, background

Table 7
Number of cancer patients treated in specialized cancer hospitals and observed mortality rates due to cancer during 1987 and 1988 in certain states in India [26]

State	No. of hospitals	1987			1988		
		Patients admitted	Patients died	Annual mortality rate (% per year)	Patients admitted	Patients died	Annual mortality rate (% per year)
Andhra Pradesh	01	No detail	No detail	No detail	2245	268	11.94
Bihar	01	637	16	2.5	560	24	4.3
Gujarat	01	1029	19	1.8	946	37	3.9
Himachal Pradesh	01	279	2	0.72	193	4	2.1
Karnataka	02	5883	348	5.9	6416	368	5.7
Kerala	01	1667	149	8.9	2168	211	9.7
Orissa	01	1752	97	5.5	1932	65	3.4
Tamil Nadu	04	13647	363	2.7	13381	338	2.5
Uttar Pradesh	01	1397	32	2.3	1506	52	3.5
West Bengal	03	4395	524	11.92	1670	207	12.39

Note: Weighted average of above mortality rates = 5.1% per year (i.e. approximately 5.1×10^{-2} per year).

individual risk factor (BIRF) has been used to account for the health risks due to selected toxic chemicals, e.g. Cd, Cr and Ni, present in the ambient environment.

Further, to convert the chances of extra cancer cases (i.e. incremental individual cancer risk) in each state into fatality per year (i.e. background individual risk factor), it was necessary to know annual mortality rate in cancer patients. To assess this, Table 7 was

Table 8
Incremental individual cancer risk from cadmium, chromium and nickel contamination in certain atmospheric environments in India (realistic estimates for mixed population)

State	Incremental individual cancer risk ($\times 10^{-6}$)			Total risk ($\times 10^{-6}$)
	Cadmium	Chromium[a]	Nickel	
Andhra Pradesh	5	22	4	31
Bihar	4	90	12	106
Chandigarh (UT)	2	140	15	157
Gujarat	6	35	2	43
Haryana	3	61	8	72
Himachal Pradesh	3	43	4	50
Karnataka	1	12	2	15
Kerala	2	13	2	17
Orissa	3	97	5	105
Punjab	2	56	6	64
Rajasthan	8	11	4	23
Tamil Nadu	2	12	2	16
Uttar Pradesh	8	48	13	69
West Bengal	8	46	4	58

Input data: Inhalation rate = 0.6 m^3/h; exposure time = 24 h per day; exposure frequency = 350 days per year; exposure duration = 60 years; body weight = 60 kg; absorption fraction = 0.25 (Cd), 0.50 (Cr), and 0.20 (Ni); averaging time period = 60 × 365 days; potency factors = 6.1 (Cd), 41 (Cr), and 1.19 (Ni).

[a] Risk estimates correspond to Cr(VI) only. The concentration of Cr(VI) has been taken as 1/7 of the total chromium (Mancuso [31]).

Table 9
Risk factors of death due to extra cancer cases induced by cadmium, chromium and nickel contamination in certain atmospheric environments in India

State	Incremental cancer risk (ICR) to an individual (from Table 8) ($\times 10^{-6}$)	BIRF[a] ($\times 10^{-6}$ per year)
Andhra Pradesh	31	1.58
Bihar	106	5.41
Chandigarh (UT)	157	8.01
Gujarat	43	2.19
Haryana	72	3.67
Himachal Pradesh	50	2.55
Karnataka	15	0.77
Kerala	17	0.87
Orissa	105	5.37
Punjab	64	3.26
Rajasthan	23	1.17
Tamil Nadu	16	0.82
Uttar Pradesh	69	3.52
West Bengal	58	2.96

[a] BIRF = incremental cancer risk to an individual (from Table 8) × weighted average annual mortality rate due to cancer in India (from Table 7) (i.e. BIRF = ICR $\times 5.1 \times 10^{-2}$ per year).

constructed on the basis of data available from the Ministry of Health and Family Welfare (MHFW), Government of India [26]. Annual mortality rates for the years 1987 and 1988, as shown in Table 7, were used to estimate the weighted average annual mortality rate of cancer patients in India. It was found that weighted average annual mortality rate in year 1987 as well as 1988 was approximately 5.06×10^{-2} per year. Thus it was taken roughly equal to 5.1% per year implying that chances of an Indian cancer patient to die is 5.1×10^{-2} per year. The estimated weighted average annual mortality rate in cancer patients at national level has been assumed to be applicable to all states of India. This estimation and assumption was made because the annual mortality rate data for cancer patients in Haryana state were not available. Thus the chances of extra cancer in different states of India (as shown in Table 8 which is based on another study carried out by the authors [19]) were converted into background individual risk factors as shown in Table 9. Here, BIRF in a state is equal to incremental (lifetime) cancer risk (ICR) in that state multiplied by above-discussed weighted average annual morality rate (i.e. BIRF = ICR $\times 5.1 \times 10^{-2}$ per year).

6. Cumulative risk factors

Tables 10 and 11 show the cumulative individual risk factors estimated by summing up IRF and BIRF assuming that their effect is additive but not the synergistic. In Haryana state, BIRF is equal to 3.67×10^{-6} per year as shown in Table 9. This figure is added to IRF at different downwind distances from the concerned industry to estimate CIRF at those distances. Then CIRF is multiplied with the population density at that downwind distance to

Table 10
Estimation of cumulative risk factors and suitability analysis of storage facility of Cl_2 at M/s XYZ-1 Ltd., Bahadurgarh (Haryana) using proposed integrated risk assessment (IRA) approach

Downwind distance (km)	IRF (year) (Table 3)	CIRF (IRF + BIRF) (year)	CGSRF (CIRF × PD) (km^{-2} per year)	Suitability[a] evaluation as per risk ranking matrix (Table 1)
0.1–0.5	1.54E−5 to 1.20E−5	1.91E−5 to 1.57E−5	1.08E−2 to 8.92E−3	U
0.5–1.0	1.20E−5 to 7.06E−6	1.57E−5 to 1.07E−5	8.92E−3 to 6.08E−3	CS
1.0–2.0	7.06E−6 to 2.53E−6	1.07E−5 to 6.20E−6	6.08E−3 to 3.52E−3	CS
2.0–3.0	2.53E−6 to 7.43E−7	6.20E−6 to 4.41E−6	3.52E−3 to 2.50E−3	S
3.0–3.4	7.43E−7 to 2.13E−7	4.41E−6 to 3.88E−6	2.80E−2 to 2.47E−2	CS
>3.4	<2.13E−7	<3.88E−6	<2.47E−2	CS

Input data: Background individual risk factor (BIRF) = 3.67×10^{-6} per year (Table 9); cumulative individual risk factor (CIRF) = IRF + BIRF; cumulative geo-societal risk factor (CGSRF) = CIRF × population density (PD); population density = 568 km^{-2} (up to 3 km), and 6359 km^{-2} (beyond 3 km).

[a] U, unsuitable; CS, conditionally suitable; and S, suitable.

Table 11
Estimation of cumulative risk factors and suitability analysis of storage facility of Cl_2 at M/s XYZ-2 Ltd., Yamuna Nagar (Haryana) using proposed integrated risk assessment (IRA) approach

Downwind distance (km)	IRF (year) (Table 4)	CIRF (IRF + BIRF) (year)	CGSRF (CIRF × PD) (km^{-2} per year)	Suitability[a] evaluation as per risk ranking matrix (Table 1)
0.1–0.5	4.71E−6 to 4.25E−6	8.38E−6 to 7.92E−6	2.90E−2 to 2.76E−2	CS
0.5–1.0	4.25E−6 to 3.15E−6	7.92E−6 to 6.82E−6	2.75E−2 to 2.36E−2	CS
1.0–2.0	3.15E−6 to 1.4E−6	6.82E−6 to 5.07E−6	2.36E−2 to 1.76E−2	CS
2.0–3.0	1.44E−6 to 8.10E−7	5.07E−6 to 4.48E−6	1.76E−2 to 1.55E−2	CS
3.0–4.0	8.10E−7 to 4.35E−7	4.48E−6 to 4.11E−6	2.41E−3 to 2.22E−3	S
4.0–5.0	4.35E−7 to 1.57E−7	4.11E−6 to 3.83E−6	2.22E−3 to 2.06E−3	S
>5.0	<1.57E−7	<3.83E−6	<2.06E−3	S

Input data: Background individual risk factor (BIRF) = 3.67×10^{-6} per year (Table 9); cumulative individual risk factor (CIRF) = IRF + BIRF; cumulative geo-societal risk factor (CGSRF) = CIRF × population density (PD); population density = 3466 km^{-2} (up to 3 km), and 539 km^{-2} (3–5 km).

[a] CS, conditionally suitable; S, suitable.

estimate the desired cumulative geo-societal risk factor. On the basis of CIRF and CGSRF (Tables 10 and 11), suitability of these industries are re-evaluated, as shown in Tables 10 and 11, using risk ranking matrix (Table 1). Here, it is to be pointed out that only chlorine storage industrial unit and Ni, Cr and Cd in ambient air were considered to estimate CIRF and CGSRF.

7. Results and discussion

IRF pertaining to hypothetical catastrophic releases of chlorine from respective industries in isolation to chronic risk posed by pollutants in ambient atmospheric environment are shown in Tables 3 and 4. It is observed that IRF belonging to M/s XYZ-1 Ltd. (Table 3) are more than the IRF pertaining to M/s XYZ-2 Ltd. (Table 4). However, due to their typical location with respect to surrounding population density, GSRF of M/s XYZ-1 Ltd. (Table 5) up to 3 km is estimated less than GSRF of M/s XYZ-2 Ltd. (Table 6). But beyond 3 km, this trend is found to be reversed. When these tables are seen in the light of risk ranking matrix (Table 1), it is found that both the industries are conditionally suitable up to 2 km. Beyond 2 km these are found to be suitable. However, when these tables (i.e. Tables 5 and 6) are reconstructed as Tables 10 and 11 to estimate CIRF and CGSRF, the suitability analysis gives different results. In this case, M/s XYZ-1 Ltd. proves to be unsuitable up to 0.5 km. Beyond 0.5 km it is conditionally suitable except between 2 and 3 km where it is found to be suitable. On the other hand, M/s XYZ-2 Ltd. proves to be conditionally suitable up to 3 km (while earlier, as shown in Table 6, it was suitable just beyond 2 km) due to increase in level of risks because of inclusion of background risk factors. After 3 km it is found to be suitable.

Figs. 1 and 2 depict the risk contours for M/s XYZ-1 Ltd. and M/s XYZ-2 Ltd., respectively, to show the extent and magnitude of different risk zones around the concerned industries. As illustrated in Fig. 1, the village Sarai Orangabad is located in insignificant risk zone while village Sankhol is in medium-risk zone. Further, village Parnalla Hasanbarh is in high-risk zone due to its close proximity to M/s XYZ-1 Ltd. This is most likely the reason why Table 10 shows this industry unsuitable within the distance of 0.5 km.

As per Fig. 2, it is the Railway Workshop that touches the low-risk zone around M/s XYZ-2 Ltd. It is to be pointed out that although M/s XYZ-2 Ltd. handles 20 t of chlorine, and located in the heart of the city surrounded by dense population, there is no high-risk zone around this industry. It is because this industry stores the chlorine in refrigerated condition (assumed with all necessary safety mechanisms) that qualifies it with low failure frequency, i.e. 3×10^{-7} per year (see Table 2), and hence poses less risk than the M/s XYZ-1 Ltd. causes to its surrounding.

Hence it is observed that the background risk factor for other toxic pollutants, along with the failure frequency and population density, alters the suitability of an industry in a given region and, therefore, cumulative or integrated risk assessment provides a better picture of risk levels around an industrial facility. This also implies that in case background risk factors are known for two or more locations, cumulative risk factors of an industry may be used to choose the site with least risk potential. Moreover, it is also inferred that all the major contributing toxic pollutants should be considered in this approach to get a realistic picture of effective risk potential of an industry.

7.1. Limitations

There is inherent uncertainty in risk calculations due to the variability in natural systems and because of the difficulty in mathematically encapsulating complex phenomena [6]. The present study has been performed in a very simplified way to illustrate the integrated approach of risk analysis. The results of this study should, therefore, be interpreted in the light of various limitations enumerated as below:

1. Risk calculations have been made for the mixed population. Separate consideration for sensitive receptors such as schools, hospitals, residential buildings, etc. [7] have not been

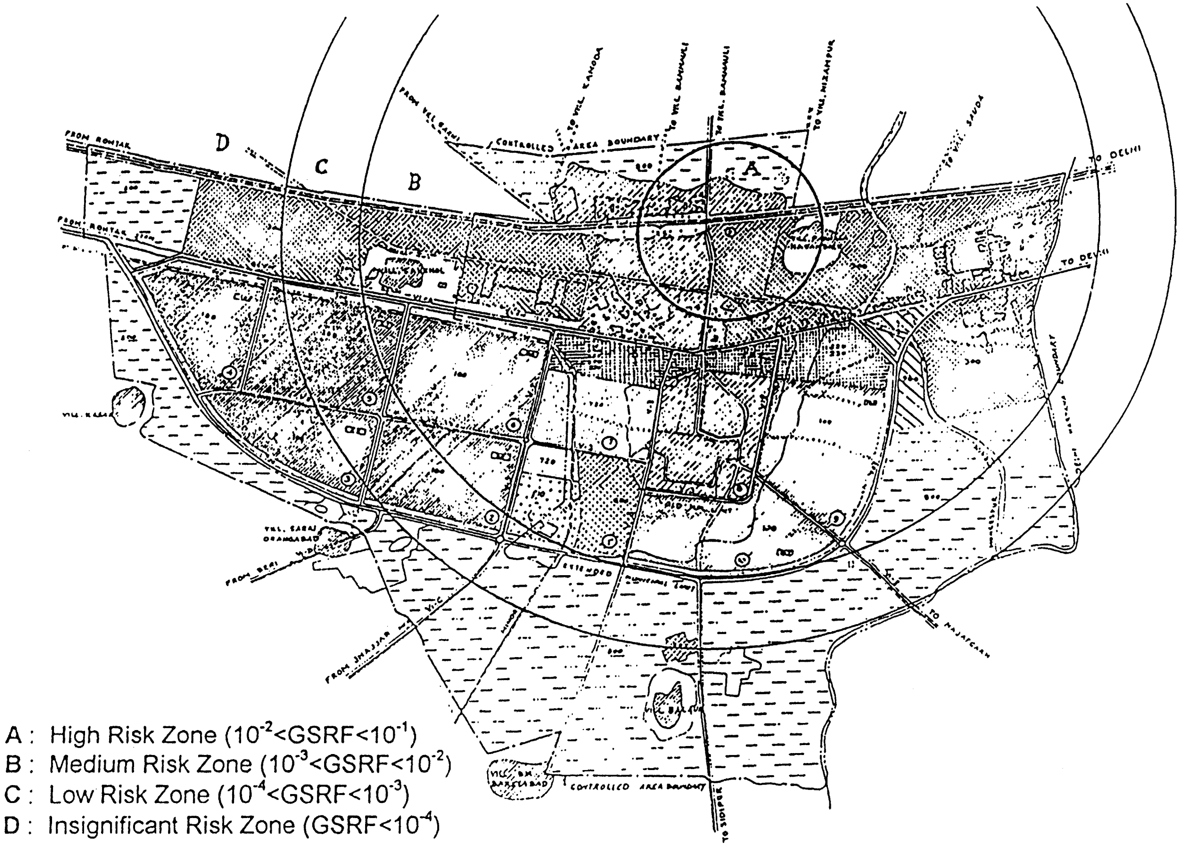

Fig. 1. Risk contours pertaining to a hypothetical catastrophic release of chlorine from M/s XYZ-1 Ltd., Bahadurgarh (Haryana) (scale: 1 cm = 0.445 km).

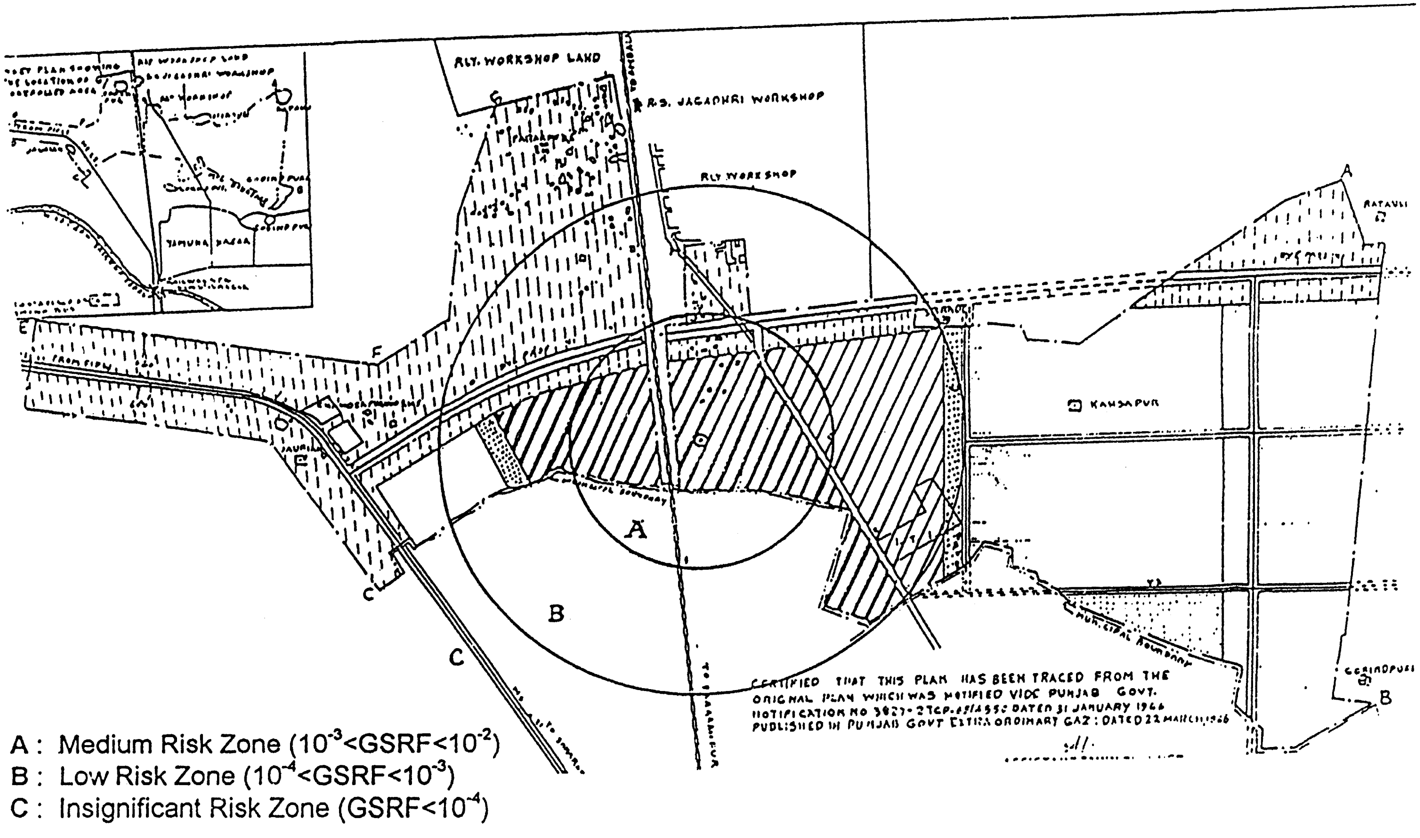

Fig. 2. Risk contours pertaining to a hypothetical catastrophic release of chlorine from M/S XYZ-2 Ltd., Yamuna Nagar (Haryana) (scale: 1 cm = 0.754 km).

taken into account. However, the general population consists of individuals with a wide range of susceptibility. For instance, some people (e.g. the very young, the elderly, pregnant women and those with acute or chronic illnesses) are likely to be more susceptible to developing adverse effects in a contaminated environment and hence liable to be more at risk than others [27,28].

2. The hypothetical industries considered in this study are assumed to be located in Haryana state of India, where calm winds (wind speed ≤2 m/s) are predominant. This wind speed corresponds to ‘A’ and ‘F’ Pasquill stability classes in day and night time, respectively [2]. In this study, only one set of stability condition (i.e. F), ambient temperature (20 °C), and wind speed (1 m/s) has been considered, to seek the conservative estimates that represent the worst-case scenario [2]. This type of combination is widely used by the government agencies for setting up stringent standards and norms for the purpose of emergency response planning and protection of public health, life and the environment. However, should the relative probabilities of stability condition, wind speed and directional frequencies were considered, risk estimates could be much different than the present ones.
3. Failure frequencies considered in this study have been derived from available literature and assumed to be representative of the storage facility conditions. However, risk estimates are quite sensitive to the failure frequency and risk estimates may portray a different picture than the present one if a frequency-based sensitivity analysis is carried out.
4. As far as the hypothetical industries are concerned, it has been assumed that only these two industries are present in that area having chlorine as one of the main toxic chemicals. There may be other industries handling or processing other kind of hazardous chemicals. In ambient air, too, there may be other toxic chemicals in addition to Cd, Cr and Ni. However, this study is to provide only an illustration how the technique could be applied for the cumulative/integrated risk assessment. Thus, there is a scope for more toxic pollutants to be included in the study after examining their presence and potential adverse effects.

8. Conclusions

In contrast to the single risks associated with single chemicals in single environmental media, an integrated risk assessment has been carried out by combining the acute as well as chronic risks due to toxic chemicals. This study of integrated risk analysis has been carried out in a most simplified way to illustrate and appreciate its broad context. For instance, as in Kumar et al. [6], the total risk has been computed by adding the risk via each pathway. However, in a real sense, integrated risk analysis is a quite complex process. In a real-world situation, an IRA may require to evaluate problems in contexts involving different sources, pathways and routes of exposure of a specific chemical. At the same time, it may also require to include the exposure assessment of other chemicals that could affect a particular risk due to synergistic effects and could pose other kind of risks in addition to the risk in question. Nevertheless, simplified integrated risk analysis, as carried out in this study, reveals that the inclusion of background risk factors in IRF related to an industry may significantly alter the siting and planning strategies of that industry.

Disclaimer

Any opinions or views expressed in this paper are those of the authors and do not necessarily reflect the position and/or official policies of the institutes they are affiliated with. Industries and storage facilities of chlorine considered in this study are hypothetical and any resemblance to any industry or facility located at Bahadurgarh and/or Yamuna Nagar cities of Haryana state (India) would be considered as a purely coincidence.

Acknowledgements

We are grateful for all the help and support extended at the Indian Institute of Technology, New Delhi (India), where first author carried out this study as part of his Ph.D. dissertation. B.R. Gurjar is grateful to the Max Planck Institute for Chemistry (MPIC) and Prof. Dr. Jos Lelieveld, Director, Atmospheric Chemistry Division, MPIC, Mainz, Germany, for providing all of the necessary support and encouragement during the revision of this paper. Earlier support provided by Technical Teachers' Training Institute, Chandigarh (India), to the first author is also acknowledged. Authors extend their special thanks to anonymous referees whose constructive suggestions have helped significantly improve the original manuscript.

References

[1] B.R. Gurjar, M. Mohan, Environmental risk analysis: problems and perspectives in different countries, Risk: Health, Safety Environ. 13 (1–2) (2002) 1–30.

[2] B.R. Gurjar, Environmental Risk Analysis for Industrial Siting, Planning and Management, Ph.D. Thesis, Centre for Atmospheric Sciences, Indian Institute of Technology, New Delhi, 1999, p. 216.

[3] F.K. Crawley, D. Ashton, Safety, health or the environment—which comes first? J. Hazard. Mater. 93 (2002) 17–32.

[4] CAPCOA, Air Toxics Hot Spots Program, Revised 1992 Risk Assessment Guidelines, Prepared by the Toxics Committee of the California Air Pollution Control Officers Association, October 1993.

[5] H. Russell, M. Fan, M. DiBartolomeis, C. Arnesen, J. Stratton, R.J. Jackson, Integrating risk management and risk communication into a risk assessment of a Medfly eradication project in California, J. Hazard. Mater. 39 (1994) 267–278.

[6] A. Kumar, R. Madasu, A. Manocha, An evaluation of smart risk and ACE2588 health risk assessment software, Environ. Progress 13 (4) (1994) N14–N19.

[7] A. Kumar, R. Madasu, A. Manocha, Refined health risk assessment for toxic emissions from a manufacturing facility, Environ. Monit. Assessment 42 (1996) 211–228.

[8] M. Kulkarni, S. Patil, Monitoring of daily integrated exposure of outdoor workers to respirable particulate matter in an urban region of India, Environ. Monit. Assessment 56 (1999) 129–146.

[9] P. Slovic, The risk game, J. Hazard. Mater. 86 (2001) 17–24.

[10] P.H. Bottelberghs, Risk analysis and safety policy developments in The Netherlands, J. Hazard. Mater. 71 (2000) 59–84.

[11] S.N. Jonkman, P.H.A.J.M. van Gelder, J.K. Vrijling, An overview of quantitative risk measures for loss of life and economic damage, J. Hazard. Mater. 99 (2003) 1–30.

[12] C.C. Travis, K.R. Obenshain, J.L. Regens, C.G. Whipple, Limitations of multimedia models for use in environmental decision-making, Environ. Monit. Assessment 71 (2001) 51–60.

[13] National Research Council (NRC), Risk Assessment in the Federal Government: Managing the Process, National Academic Press, Washington, DC, 1983.
[14] US Environmental Protection Agency, MMSOILS: Multimedia Contaminant Fate, Transport, and Exposure Model, Documentation and User's Manual, Version 4.0, Office of Research and Development, Washington, DC, 1996.
[15] C.R. Krishnamurti, P. Vishwanathan (Eds.), Toxic Metals in the Indian Environment, McGraw-Hill, New Delhi, 1991.
[16] K.P. Mahendra, India's Population: Heading Towards a Billion, B.R. Publishing, Delhi, 1991.
[17] United States Environmental Protection Agency, Risk Assessment Guidance for Superfund: Human Health Evaluation Manual, vol. 1, part A, Interim Final EPA/540/1/89/002, Office of Emergency and Remedial Response, USEPA, Washington, DC, 1989.
[18] G.M. Masters, Introduction to Environmental Engineering and Sciences, Prentice-Hall, New Delhi, 1998.
[19] B.R. Gurjar, M. Mohan, Potential health risks due to toxic contamination in the ambient environment of certain Indian states, Environ. Monit. Assessment 82 (2003) 203–223.
[20] W.F. Kenney, Process Risk Management System, VCH, New York, 1993.
[21] R.F. Griffiths, A.S. Harper, A speculation on the importance of concentration fluctuations in the estimation of toxic response to irritant gases, J. Hazard. Mater. 11 (1985) 369–372.
[22] D.J. Finney, Probit Analysis, third ed., Cambridge University Press, London, 1971.
[23] M. Mohan, B.R. Gurjar, Risk-based IIT-TPQ model to establish threshold planning quantities of hazardous substances, J. Air Waste Manage. Assoc.
[24] Statistical Abstracts of Haryana 1995–1996, Issued by Economic and Statistical Organization, Planning Department, Government of Haryana, Publication No. 568, 1997.
[25] T.V.B.P.S. Ramakrishna, Air Quality Models for Indian Meteorological Conditions in Urban Cities of India, Ph.D. Thesis, Indian Institute of Technology, New Delhi, 1997.
[26] Health Information of India Central Bureau of Health Intelligence, Directorate General of Health Services, Ministry of Health and Family Welfare, Government of India, Nirman Bhawan, New Delhi, 1989.
[27] R. Raghunath, R.M. Tripathi, A. Vinod Kumar, A.P. Sathe, R.N. Khandekar, K.S.V. Nambi, Assessment of Pb, Cd, Cu, and Zn exposures of 6- to 10-year-old children in Mumbai, Environ. Res. Sec. A 80 (1999) 215–221.
[28] Air Toxics Hot Spots Program: Risk Assessment Guidelines, Part III, Technical Support Document for the Determination of Noncancer Chronic Reference Exposure Levels, Air Toxicology and Epidemiology Section, Office of Environmental Health Hazard Assessment, California Environmental Protection Agency (CEPA), Oakland, CA, USA, URL: http://www.oehha.ca.gov/air/chronic_rels/pdf/relsP32k.pdf.
[29] Risk Analysis of UPPC—Auraiya, Document no. XX, Rev. no. A, Engineers India Ltd., New Delhi, 1998.
[30] Environmental Risk Assessment of PACL, Punjab Alkalies and Chemicals Ltd. (PACL), Naya Nangal, Punjab, India, 1996.
[31] T.F. Mancuso, Consideration of chromium as an industrial carcinogen, in: Proceedings of the International Conference on Heavy Metals in the Environment, Toronto, Ont., Canada, 27–31 October 1975, pp. 343–356.